X-Raying the MOJAVE Sample of Compact Extragalactic Radio Jets

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Abstract. The MOJAVE sample is the first large radio-selected, VLBI-monitored AGN sample for which complete X-ray spectral information is being gathered. We report on the status of *Swift* survey observations which complement the available archival X-ray data at 0.3-10 keV and in the UV with its XRT and UVOT instruments. Many of these 133 radio-brightest AGN in the northern sky are now being observed for the first time at these energies. These and complementary other multi-wavelength observations provide a large statistical sample of radio-selected AGN whose spectral energy distributions are measured from radio to gamma-ray wavelengths, available at the beginning of GLAST operations in 2008. Here, we report the X-ray spectral characteristics of 36 of these previously unobserved MOJAVE sources. In addition, the number of MOJAVE sources detected by the BAT instrument in the hard X-ray band is growing: we report the detection of five new blazars with BAT.

Keywords: galaxies: active — galaxies: jets — galaxies: individual (NRAO 140, PKS B 1222+216, PKS B 1510−089, 3C 345, PKS B 2126−158)
PACS: 95.85.Bh, 95.85.Nv, 95.85.Pw, 98.54.Cm

X-RAY OBSERVATIONS OF MOJAVE AND RELEVANCE FOR GLAST

Radio-loud core-dominated (RLCDs) active galactic nuclei (AGN) are an important class of extragalactic supermassive black-hole systems whose bright compact radio cores can be imaged at milliarcsecond resolution with Very-Long-Baseline Interferometry (VLBI). The vast majority of all RLCDs are blazars, BL Lac objects and flat-spectrum radio quasars, but also some Seyfert and broad-line radio galaxies exhibit bright compact radio cores with powerful relativistic jets. Since 1994, the VLBA 2 cm Survey [1] and its follow-up MOJAVE ([4], and Lister 2007, these proceedings) have been monitoring the structural changes in the jets of more than 200 AGN with bright compact radio cores. At present, the MOJAVE monitoring regularly observes 192 objects, including a flux-density limited, radio-selected, statistically complete sub sample of the 133 radio-brightest compact extragalactic jets in the northern sky: the MOJAVE sample[1].

Compact radio jets of blazars, typically show ejections of relativistic plasma every few months to years related to the formation of new jet component that travel at superluminal speeds of up to $\sim 30\,c$ down the jet. On the other hand, blazars are known to be bright and rapidly variable gamma-ray sources. The connection of jet-formation events to the broadband-SED variability of blazars is an important aspect of both the MOJAVE and GLAST project and calls for multi-wavelength coordination with other large surveys at intermediate observing wavelengths. In order to be able to react *swiftly* to gamma-ray flares detected by GLAST, to plan and coordinate multiwavelength observations, it is important to gather broadband SED information about the objects of interest in advance to the arrival of first GLAST data. In our case of a radio-selected AGN sample that is continuously monitored with VLBI and single-dish telescopes (see Fuhrmann et al., these proceedings), *Swift* with its optical/UV (UVOT) and X-ray (XRT) capabilities, is ideally suited to provide these SED data to connect the radio and gamma-ray bands.

[1] See the program website for a detailed description of the selection criteria and a regularly updated list of the full sample: `http://www.physics.purdue.edu/astro/MOJAVE/`

Swift X-Ray Survey of the MOJAVE Sample

An archival X-ray spectral survey of all publicly available data for MOJAVE sources has been conducted by [2]. This so-called 2cm-X-Sample currently contains 50 out of 133 MOJAVE sources. 17 additional sources have been observed by *Swift* before the beginning of our project. This still leaves us with 66 of the radio brightest blazars in the northern sky having never been observed with an X-ray spectroscopic mission above 2 keV.

We have started a program to observe all the so-far unobserved MOJAVE sources with the *Swift* XRT as part of the *Swift* blazar key project. This will produce the first statistically complete large radio-selected sample of blazars and other RLCDs. The observations will complete the data base of the 2 cm-X-Sample of photon indices, source-intrinsic absorbing column densities and X-ray luminosities. It will allow for the first time statistically robust radio/X-ray correlation analyses of these quantities with relativistic jet parameters from VLBI observations. In addition, because of the ongoing MOJAVE monitoring observations, the Swift data will naturally yield to an unprecedented set of quasi-simultaneous broadband SED data from the radio, optical/UV and X-ray regime.

New X-ray spectra for 36 MOJAVE sources:. Our program started in November 2006. At the time of writing (March 2007), 94 objects have been observed. We concentrate here on completed observations (i.e., $>\sim 10$ ksec) of sources from the statistically complete MOJAVE sample of the 133 radio-brightest, compact AGN in the northern sky. The XRT data were acquired mainly in Photon Counting (PC) mode. We used the program XSELECT to extract source and background counts from the cleaned event lists processed at Swift Science Data Center (SDC). The source spectrum is calculated from a circular region with the radius of 47 arcsec, while the background region is selected as an annulus of the outer radius of 150 arcsec and the inner radius of 70 arcsec. A pile-up correction is applied when the count rate exceeds 0.6 counts/s by excluding the central area of 7 arcsec radius. RLCDs are found to have comparably simple X-ray spectra, typically well-approximated by an absorbed power law. Therefore, we performed a spectral fit to the time-averaged spectra with an absorbed power-law model. As of March 2007, we have completed the observations of 36 out of 66 previously unobserved MOJAVE sources. In Table 1, we report for the first time the basic X-ray spectral characteristics of these objects in the $(0.3-10)$ keV band. Errors quoted are at the 90% confidence level.

All 36 objects have been detected with the XRT in 10 ksec exposures. In some cases of either very low X-ray flux or peculiar spectral or temporal source behavior, we have obtained follow-up observations to improve the photon statistics or to trace source variability over a longer time range. We find an average value of $\Gamma_{\rm ave} = 1.8$, with a standard deviation of 0.2 similar to values of ~ 1.6–1.7, which are typically found in the old 2 cm-X-Sample ([2] and in prep.). The absorbing column densities determined have been compared to the expected Galactic absorption values from the LAB survey [3]. Significant excess absorption was found in 9 sources ($< 10^{21}$ cm^{-2} in all cases; compare Table 1).

New hard X-ray detections of five blazars with BAT:. The Burst Alert Telescope (BAT) is the hard X-ray instrument on-board *Swift* and is a continuously operating all-sky hard X-ray monitor and survey instrument [5]. Prior to the beginning of our program, 17 blazars were detected by BAT (Tueller et al., in prep.). These sources were found via “blind search” of the whole sky, using a sliding-cell detection method (BATCELLDETECT), requiring at least $\sim 5\sigma$ significance of each individual source. We have conducted a search of the BAT data base, based on the first nine months of observations, aiming for those MOJAVE sources for which our *Swift* XRT fill-in observations did yield an extrapolated $(14-195)$ keV flux above or close to $\sim 10^{-11}$ erg s^{-1} cm^{-2}. This criterion was met for 19 objects which we assign a ranking number, according to the value of the extrapolated flux (rank 1 for the highest to rank 19 for the lowest extrapolated flux). We found significant excess flux at the positions of five blazars: NRAO 140 (Rank 1, $F_{\rm extrapol.} = 4.73 \times 10^{-11}$ erg s^{-1} cm^{-2}, 5.1σ), PKS B 1510−089 (Rank 2, $F_{\rm extrapol.} = 3.68 \times 10^{-11}$ erg s^{-1} cm^{-2}, 4.0σ), PKS B 2126−158 (Rank 3, $F_{\rm extrapol.} = 3.40 \times 10^{-11}$ erg s^{-1} cm^{-2}, 3.4σ), 3C 345 (Rank 6, $F_{\rm extrapol.} = 2.61 \times 10^{-11}$ erg s^{-1} cm^{-2}, 3.7σ), and PKS B 1222+216 (Rank 19, $F_{\rm extrapol.} = 9.36 \times 10^{-12}$ erg s^{-1} cm^{-2}, 3.8σ). A deeper analysis of the hard X-ray properties of these blazars is currently being performed. Tentative signals ($\lesssim 3\sigma$) are found at the position of the 5th-ranked source PKS B 1127−145, the 10th-ranked source PKS B 0403−132, and the 16th-ranked source PKS B 2008−159.

The rank distribution demonstrates that our method preferentially picks up those blazars that are just below the BAT detection threshold of a few times 10^{-11} erg s^{-1} cm^{-2}. The fact that a significant signal is registered at the position of the relatively faint source PKS B 1222+216 but not from comparably bright objects like the 4th-ranked source PKS B 0723−08 suggests that X-ray variability and spectral breaks above 10 keV may play an important role. We expect to detect more MOJAVE sources with BAT in the future, in particular with increased sensitivity in later stages of the BAT mission.

TABLE 1. X-ray spectral fitting parameter of MOJAVE sources

Source IAU B 1950	Alt. Name	Exposure [ksec]	Photon Index	N_H $[10^{22}\,cm^{-2}]$	$N_{H,Gal}$ $[10^{22}\,cm^{-2}]$	χ^2_{red}/dof	$F_{(0.3-10)\,keV}$ $[erg\,s^{-1}\,cm^{-2}]$
0016+731		8950	$1.75^{+0.23}_{-0.21}$	$0.25^{+0.08}_{-0.07}$	0.19	0.59/22	3.30×10^{-12}
0202+149		8983	$1.92^{+1.43}_{-1.02}$	<0.65	0.05	0.74/3	3.04×10^{-13}
0224+671	4C +67.05	12112	$1.89^{+0.39}_{-0.34}$	$0.58^{+0.25}_{-0.19}$	0.40	0.44/9	1.23×10^{-12}
0336−019	CTA 26	10653	$1.94^{+0.31}_{-0.27}$	$0.08^{+0.07}_{-0.06}$	0.06	1.27/11	1.17×10^{-12}
0403−132		9503	$1.56^{+0.14}_{-0.13}$	$0.06^{+0.04}_{-0.03}$	0.04	0.78/37	5.02×10^{-12}
0529+075		19537	$1.86^{+0.19}_{-0.18}$	$0.30^{+0.19}_{-0.18}$	0.17	1.36/31	1.92×10^{-12}
0529+483		9124	$1.28^{+0.79}_{-0.63}$	<0.37	0.25	0.87/2	9.21×10^{-13}
1124−186		9515	$1.99^{+0.45}_{-0.36}$	$0.07^{+0.08}_{-0.06}$	0.04	1.26/8	9.71×10^{-13}
1150+812		11244	$1.74^{+0.45}_{-0.39}$	<0.07	0.05	1.24/6	8.48×10^{-13}
1324+224		13330	$1.78^{+0.19}_{-0.17}$	$0.07^{+0.05}_{-0.04}$	0.02	0.86/24	2.01×10^{-12}
1417+385		11730	$2.11^{+0.52}_{-0.41}$	$0.08^{+0.10}_{-0.07}$	0.01	0.46/5	5.56×10^{-13}
1504−167		12571	$1.80^{+0.70}_{-0.54}$	<0.22	0.07	0.64/7	3.34×10^{-13}
1538+149	4C +14.60	9527	$2.28^{+0.49}_{-0.40}$	$0.12^{+0.09}_{-0.07}$	0.03	0.60/11	1.17×10^{-12}
1546+027		9657	$1.76^{+0.17}_{-0.16}$	$0.07^{+0.04}_{-0.04}$	0.07	1.03/31	3.45×10^{-12}
1606+106	4C +10.45	49342	$1.43^{+0.10}_{-0.09}$	$0.04^{+0.02}_{-0.02}$	0.04	0.93/73	1.92×10^{-12}
1611+343	DA 406	9789	$1.77^{+0.34}_{-0.27}$	<0.11	0.01	0.74/9	1.18×10^{-12}
1637+574		10140	$1.91^{+0.14}_{-0.13}$	$0.05^{+0.03}_{-0.03}$	0.01	0.90/40	3.95×10^{-12}
1638+398	NRAO 512	12267	$1.49^{+0.29}_{-0.23}$	<0.04	0.01	1.17/5	7.58×10^{-13}
1726+455		10722	$2.04^{+0.36}_{-0.31}$	$0.15^{+0.08}_{-0.07}$	0.02	1.23/12	1.20×10^{-12}
1730−130	NRAO 530	9912	$1.46^{+0.32}_{-0.29}$	$0.29^{+0.14}_{-0.11}$	0.18	0.98/12	2.18×10^{-12}
1739+522	4C +51.37	10304	$1.55^{+0.23}_{-0.20}$	$0.07^{+0.06}_{-0.05}$	0.03	0.72/18	2.30×10^{-12}
1741−038		9927	$1.72^{+0.34}_{-0.31}$	$0.41^{+0.18}_{-0.14}$	0.18	0.72/12	2.01×10^{-12}
1751+288		9772	$1.77^{+0.45}_{-0.39}$	$0.12^{+0.11}_{-0.09}$	0.05	0.83/7	1.10×10^{-12}
1758+388		9711	$2.14^{+1.30}_{-0.90}$	<0.38	0.03	0.70/4	2.84×10^{-13}
1800+440		10098	$1.75^{+0.17}_{-0.16}$	$0.04^{+0.03}_{-0.03}$	0.03	0.98/31	3.36×10^{-12}
1849+670		9952	$2.07^{+0.31}_{-0.28}$	$0.17^{+0.08}_{-0.07}$	0.05	1.65/16	1.71×10^{-12}
1936−155		9929	$2.25^{+0.60}_{-0.49}$	$0.24^{+0.17}_{-0.12}$	0.08	0.50/5	7.15×10^{-13}
1958−179		8997	$1.84^{+0.29}_{-0.27}$	$0.16^{+0.09}_{-0.07}$	0.07	0.90/14	1.95×10^{-12}
2005+403		11986	$1.69^{+0.29}_{-0.27}$	$0.50^{+0.19}_{-0.15}$	0.48	0.88/15	1.98×10^{-12}
2008−159		9657	$1.75^{+0.13}_{-0.12}$	$0.14^{+0.04}_{-0.03}$	0.06	1.08/48	5.71×10^{-12}
2021+317	4C +31.56	28861	$1.96^{+1.04}_{-0.65}$	$1.21^{+0.95}_{-0.76}$	0.52	1.98/4	3.24×10^{-13}
2021+614		17562	$0.87^{+1.26}_{-0.88}$	<2.01	0.14	0.51/3	2.14×10^{-13}
2037+511	3C 418	10189	$1.70^{+0.45}_{-0.38}$	$0.66^{+0.37}_{-0.25}$	0.54	0.91/11	2.02×10^{-12}
2136+141	OX 161	10140	$1.43^{+0.28}_{-0.25}$	<0.15	0.06	0.48/11	1.67×10^{-12}
2201+171		9585	$1.85^{+0.34}_{-0.30}$	$0.10^{+0.09}_{-0.07}$	0.05	0.89/7	9.80×10^{-13}
2216−038		9650	$1.82^{+0.33}_{-0.29}$	$0.07^{+0.08}_{-0.06}$	0.06	1.16/12	1.53×10^{-12}

ACKNOWLEDGMENTS

The authors wish to acknowledge the efforts and contributions of the *Swift* BAT and MOJAVE teams.

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